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Goal-Oriented Down-Selection Criteria for Fusion Space Propulsion Based on a Concept's Physical Limitations

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Goal-oriented down-selection criteria for fusion space propulsion based on a concept's physical limitations

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Abstract:

We propose that rational down-selection criteria for fusion space propulsion should be based on the goals for NASA's future missions, and in particular, on performance goals. Specifically, if the ultimate long-range performance for a certain fusion concept for a particular mission cannot exceed that expected for an economically and environmentally viable fission-propulsion system, which is obviously based on a more mature technology than the fusion system, NASA should not spend the time and resources required to develop that fusion system. We also propose consideration of inherent physical constraints for each space-propulsion concept, because the physical constraints can limit a concept's ultimate performance. Such constraints can thus make a concept subject to down-selection even though there are currently large uncertainties in a particular system's ultimate performance, projected cost of development, or even "proof-of-principle" status.

One way to impose such goal-oriented criteria is to require all viable fusion concepts for a given mission to have an alpha (i.e., a ratio of dry mass to jet power) less than a maximum that corresponds to the performance of the fission systems. Specifically, using a Mars roundtrip as an example, we discuss how physical limitations in target gain and nozzle physics can preclude a concept achieving the required alpha. This goal-oriented approach for down-selection based on physical constraints can help NASA know up front where to wisely spend its R&D funds.

1. Introduction

When NASA is presented with what will certainly be a large number of candidate concepts that it could develop for fusion space propulsion, NASA will undoubtedly want to use credible selection criteria at some point to reduce the number to a manageable few. What the down-selection criteria should be, and when they should be imposed, are of course subject to much debate.

One way of typically categorizing the concepts is according to past DoE funding—that is, whether the concept is "mainline" (ICF, MCF) or one of the innovated confinement concepts (ICCs) that has had little funding so far from DoE (MTF, IEC, etc.). However, an ICC concept, being in its infancy, is not well understood. It is therefore easy to oversimplify its development path and misestimate its development cost because the obstacles that would impede its development and expand its development costs are simply not known. On the other hand, many of the ICCs are worthy of support to help them reach a level where a "proof of principle" experiment could identify some of their true worth. What, then, should be the basis for NASA's down-selection criteria in the face of so many uncertainties?

2. Keeping our eyes on the goal

One basis that should be paramount to NASA in formulating down-selection criteria for a certain class of missions is whether the concept can *ever* serve NASA better than existing technologies. Specifically, consider a known fission-propulsion system that is economically and environmentally viable for a certain mission. Then, if the ultimate long-range performance for a particular fusion concept cannot exceed that expected for the fission system, which is obviously based on a more mature technology than the fusion system, common sense tells us that NASA should not spend the time and resources required to develop that fusion system. Consider, for example, a piloted roundtrip to Mars. A nuclear thermal rocket (or very advanced nuclear electric propulsion system) is expected to yield a roundtrip flight duration of about 1.0 to 1.5 years, so fusion, to be useful, must do "better" in order to justify the time and cost to develop the fusion systems. The usefulness of fusion is not merely to provide shorter flight durations, per se, but also to help the crew avoid (1) the physiological deterioration arising from zero-gee exposures lasting more than 100 days, and (2) the significant onset of leukemia and other cancers arising from exposures to the cosmic radiation exceeding one year. We might also consider the environmental advantages of fusion systems (e.g., less radioactivity hazard for material launched through the atmosphere).

Therefore, although NASA must consider many factors, one criterion for down-selection is whether a credible systems analysis (or even a basic physics assessment) can show that the concept could *ever* reach a level of performance better than what nuclear fission is expected to provide. This criterion can be made quantitative by requiring that the estimated flight duration be shorter than that expected for fission systems. Instead of using flight duration, we may also use the primary dynamical figure of merit for flight duration, namely, alpha (α), which we define here as the ratio of the dry mass to the jet power in kg/kW. For example, for a Mars roundtrip, computer calculations indicate that the α corresponding to a total flight duration of roughly one year is about 5 to 10 kg/kW if all onboard systems (driver, power, radiator, etc. systems) are 100% efficient, or about 1 to 2 kg/kW for systems with typical inefficiencies. The alpha for known fission systems for a Mars roundtrip is thus of order unity, $\alpha_{fission} = O(1)$. Therefore, a goal-oriented criterion for a Mars roundtrip can be stated as requiring a candidate fusion concept to be modified or even eliminated (at some point) if a credible systems analysis shows that its flight system cannot achieve an $\alpha < O(1)$. To support any fusion concept having $\alpha >> 1$ would hence be merely of academic interest.

3. The Role of Physical Constraints

The limitation set by certain physical constraints can force a minimum value for α that is larger than unity, and hence affect the down-selection process. For example, as we will show in Section 4, hybrid-plume concepts attempting to decrease α by the addition of cold expellant in the nozzle are now known to be ineffective because the difficulty of attaining a thermalized mixture of the cold and hot components within the nozzle region limits the jet efficiency to a value near zero (i.e., α near infinity). Thus, an ICF system like VISTA should have the lowest α for the mainline DoE approaches because (1) magnetic-confinement-fusion (MCF) systems tend to be more massive than ICF systems, and even more importantly, (2) MCF systems tend to be thrust-limited because the maximum-power constraint limits the maximum value for the mass flow rate.

Constraints for ICC systems can also be important. This is not well appreciated because some of the ICCs might have a dry mass of only tens of metric tons (i.e., between 10^4 and 10^5 kg). One is therefore tempted to believe that getting $\alpha < 1$ should be easy because the jet power need only exceed 10^4 to 10^5 kW. However, getting $\alpha < O(1)$ is not as easy as one might think, as the following arguments demonstrate.

A system's specific impulse I_{sp} is defined by the magnitude of the thrust F projected along the rearward direction and the mass flow rate (dm/dt),

$$gI_{sp} = \frac{|\vec{F}|}{\left(dm/dt\right)} \quad (1)$$

where g is 9.8 m / s^2. The jet power P_{jet} is then

$$P_{jet} = \frac{|\vec{F}|^2}{2\left(dm/dt\right)} = \left(\frac{1}{2}\right)\left(dm/dt\right)\left(gI_{sp}\right)^2 \tag{2}$$

The jet efficiency ε_{jet} is defined as

$$\varepsilon_{jet} = \frac{P_{jet}}{P_{input}} \tag{3}$$

where P_{input} is the power inputted to the jet (not the power inputted to the engine). Through P_{jet}, the jet efficiency includes degradations in jet power arising from such things as non-mono-energetic exhaust velocity distributions, non-axial exhaust emissions requiring geometric projections of momenta on the thrust axis, non-mono-atomic-weight exhaust distributions, and coupling (drag) effects.

For fusion systems pulsed at a reprate ν Hz with driver energy E_{dr} and fusion energy gain G, the input power in Eq. (3) is

$$P_{input} = \nu E_{dr}(G+1) \tag{4}$$

where the "plus one" accounts for the driver energy itself. Using Eqs. (3) and (4) to obtain P_{jet} and equating the result with the value in Eq. (2), we find that the specific impulse is

$$gI_{sp} = \sqrt{\frac{2\nu E_{dr}(G+1)\varepsilon_{jet}}{\left(dm/dt\right)}} \tag{5}$$

This result demonstrates that the specific impulse is dependent on the jet efficiency. Even for a system with a mono-energetic axial exhaust velocity v_{ex}, the I_{sp} is still dependent on the jet efficiency because the jet power is, from Eqs. (3) and (4), simply

$$P_{jet} = \nu E_{dr}(G+1)\varepsilon_{jet} = \left(\frac{1}{2}\right)\left(dm/dt\right)v_{ex}^2\varepsilon_{jet} \qquad \text{(single } v_{ex}\text{)} \tag{6}$$

so, making this substitution for the numerator in Eq. (5), we get

$$gI_{sp} = v_{ex}\sqrt{\varepsilon_{jet}} \qquad \text{(single } v_{ex}\text{)} \tag{7}$$

A concept's I_{sp} should thus include the jet-efficiency factor.

For the general case, the quantity α can be defined using Eqs. (2) and (5) as

$$\alpha = \frac{m_{dry}}{P_{jet}} = \frac{m_{dry}}{\frac{1}{2}\left(\frac{dm}{dt}\right)\left(gI_{sp}\right)^2} = \frac{m_{dry}}{\nu E_{dr}(G+1)\varepsilon_{jet}} \tag{8}$$

where E_{dr} is in kJ and m_{dry} is in kg. The criterion mentioned above requiring α to be less than of order 1 kg / kW thus demands the fusion gain G to be larger than a minimum G_{min} that can be established from Eq. (8):

$$(G+1) > (G_{\min}+1) = \frac{m_{dry}}{\nu E_{dr}\varepsilon_{jet}} \qquad (9)$$

This is a key equation, because differing technologies place different restrictions on the maximum gain achievable.

At this point, we might be tempted to insert a dry mass of 10^4 to 10^5 kg for some ICC having (e.g.) a reprate of 30 Hz, a driver energy of 10^3 kJ, and a jet efficiency of 40%. We would then obtain a result for (G_{min} + 1) of 0.8 to 8, which is well within the capability of many ICC systems. However, this is an incorrect result—we cannot independently choose the above numbers because they violate another constraint. To see this, and correctly apply Eq. (9), we must first examine this other constraint.

Let f be the recycled power fraction. Obviously, we need f << 1; for example, the power fP_{jet} recycled to operate a driver with efficiency ε_{dr} (as well as other equipment) must be rather small compared to the jet power itself. Considering a Mars trip and using $\alpha_{fission}$ = 1 in the first part of Eq. (8), we find that this constraint means the following for the fusion driver:

$$P_{dr} = \frac{\nu E_{dr}}{\varepsilon_{dr}} << P_{jet} = \frac{m_{dry}}{\alpha} > \frac{m_{dry}}{1\,kg/kW} \qquad \text{(Mars trip)} \qquad (10)$$

Ignoring the power recycled for other equipment, we can calculate f by taking the ratio of the terms at the ends of Eq. (10) and obtain

$$f = \frac{\nu E_{dr}}{\varepsilon_{dr} m_{dry}} << 1 \qquad \text{(Mars trip)} \qquad (11)$$

where again E_{dr} is in kJ and m_{dry} is in kg, so Eq. (9) becomes

$$(G+1) > (G_{\min}+1) = \frac{1}{f\varepsilon_{jet}\varepsilon_{dr}} >> 1 \qquad \text{(Mars trip)} \qquad (12)$$

Jet efficiencies for fusion systems are typically about 1 / 3 from geometric considerations alone (i.e., from projections of the exhaust velocities on the thrust axis). Driver efficiencies (at least for ICF systems) are near 10% (but might be as much as 40% for some ICCs), and f should really be less than roughly a few percent. Therefore, according to Eq. (12), the fusion gain for any viable concept must be at least ~250 to just match the performance for fission systems. Computer calculations for VISTA agree with this rough assessment, and show that performance doesn't really shine in comparison with that for fission systems until G is greater than about 500. In any case, for pulsed fusion systems where target gain is a well-defined quantity, we have

G > ~250 for Mars trips (13)

This is an important result. For example, an MTF system has G of at most about 70 because it is a volumetrically ignited burn. Therefore, to be considered competitive (i.e., viable), a credible systems analysis for a flight system powered by MTF must demonstrate the required performance—it cannot be assumed—because, given everything else the same, MTF systems will not be able to compete with fission systems. This conclusion may affect the down-selection process.

4. Dynamical Constraints for Nozzles With Mixed Flows

The jet efficiency for any viable concept must be large compared to some number like 10% to achieve $\alpha < O(1)$. Such performance is very difficult for certain magnetic-fusion concepts which add extra expellant in the nozzle region, because the added expellant stream does not thermalize with the hot fusion plasma emissions within the nozzle region. This is especially true in the typical case of non-collisional flows. The main reason for this is that α is near zero for exhaust-velocity distributions that are significantly bimodal—that is, for an exhaust with two distinct velocity components.

To understand why this is so, consider a simple exhaust that has two purely axial and constant velocity components: a low-density central core with high velocity v_c and low mass flow rate dm_c/dt, and a high-density annular outer region with low velocity v_a and high mass flow rate dm_a/dt. The thrust F can then be obtained from the momentum-conservation equation:

$$F = v_c \, {dm_c}/{dt} + v_a \, {dm_a}/{dt} \tag{14}$$

so from Eq. (2),

$$P_{jet} = \frac{\left[v_c \, {dm_c}/{dt} + v_a \, {dm_a}/{dt} \right]^2}{2\left({dm_c}/{dt} + {dm_a}/{dt} \right)} \tag{15}$$

The input power can be obtained from the energy-conservation equation:

$$P_{input} = \frac{1}{2}\left[\left({dm_c}/{dt} \right) v_c^2 + \left({dm_a}/{dt} \right) v_a^2 \right] \tag{16}$$

Inserting Eqs. (15) and (16) into Eq. (3) defining the jet efficiency, we obtain

$$\varepsilon_{jet} = \frac{\left[v_c \, {dm_c}/{dt} + v_a \, {dm_a}/{dt} \right]^2}{\left({dm_c}/{dt} + {dm_a}/{dt} \right)\left[\left({dm_c}/{dt} \right) v_c^2 + \left({dm_a}/{dt} \right) v_a^2 \right]} \tag{17}$$

Suppose a fusion core has parameters:

$dm_c / dt = 0.001$ kg / s

$v_c = 10^6$ m / s

while the annular gas added in the nozzle has parameters:

$dm_a / dt = 10.00$ kg / s

$$v_a = 10^3 \text{ m/s}$$

Then, inserting these numbers into Eq. (17), we find the jet efficiency to be only 1.2%. Alternately, suppose a fusion core has parameters:

$$dm_c / dt = 0.001 \text{ kg/s}$$
$$v_c = 10^5 \text{ m/s}$$

while the annular gas added in the nozzle has parameters:

$$dm_a / dt = 1.00 \text{ kg/s}$$
$$v_a = 10^1 \text{ m/s}$$

Then, inserting these numbers into Eq. (17), we find the jet efficiency to be only 0.12%.

Thus, if the nozzle gases in a hybrid-plume concept do not equilibrate (i.e., do not come into thermal equilibrium to form one component in velocity space), the jet efficiency can be very small. Thermal equilibrium, on the other hand, allows high jet efficiency. For example, a Maxwell-Boltzmann distribution allows the jet efficiency to be as high as ~85%, whereas a mono-energetic beam can have a jet efficiency of ≤100%.

Unfortunately, most hybrid-plume fusion concepts have non-collisional core components that will not thermalize with added mass streams within the nozzle. For this reason, it is not advisable to add extra (cold) expellant to an exiting (hot) plasma component to vary the I_{sp} or in fact to do anything except degrade the jet efficiency. Therefore, hybrid-plume concepts will generally not outperform fission concepts, and may hence be non-competitive. The basic physics point here is that, to achieve the $\alpha < O(1)$ constraint, expellant must usually be *directly* heated with the fusion energy itself (e.g., as a target envelope) or accelerated as one mass stream after the fusion energy has been converted through a power-conversion process (e.g., as for IEC).

With these dynamical constraints in mind, we now know that any concept attempting to mix components in a nozzle region must demonstrate that thermalization will occur, or at least that the concept can achieve $\alpha < O(1)$, or the concept must be discarded from consideration for roundtrips to Mars.

5. Discussion and Conclusions

We propose that one fundamental goal-oriented down-selection criterion for fusion space propulsion is to require a concept's ultimate performance to exceed that expected for fission propulsion systems. This criterion can be stated quantitatively by requiring a fusion system to have a shorter flight duration for any given mission under consideration. The criterion can then be restated in terms of α, the ratio of the dry mass to jet power in kg / kW, by simply requiring $\alpha < \alpha_{fission}$.

We demonstrated that physical limitations of a concept can limit the minimum α and hence the concept's ultimate performance capability. Specifically, for a roundtrip to Mars, the fundamental criterion requires $\alpha < O(1)$ because $\alpha_{fission} = O(1)$. We then showed that a concept based on pulsed emissions is not expected to satisfy this criterion unless its "target" gain G is greater than roughly 250. We also showed that a "steady-state" (non-pulsed) concept is not expected to achieve $\alpha < O(1)$ by adding cold expellant in a nozzle region. Thus, NASA should normally expect pulsed concepts with $G << 250$ and steady-state concepts with hybrid plumes to be unable to deliver the performance required to outperform fission systems. In other words, the physical limitations of such concepts make them unviable in terms of the ultimate goals for NASA mission strategies.

What this really means is that concepts that appear up front to be unable to satisfy $\alpha < \alpha_{fission}$ can avoid being discarded outright only by adding new conceptual features, or by demonstrating through a detailed systems analysis that they indeed do satisfy the criterion. While a concept is in the state of being unable to satisfy $\alpha < \alpha_{fission}$, it can be placed in a "questionable" class, which is of course distinct from the class of concepts that appear to be able to satisfy the criterion. NASA may then choose to discard the questionable concepts, or proceed to a credible systems analysis.

Caution is needed, however, because (1) a systems analysis may be required to determine a credible α, and (2) the quantitative statement of the criterion in terms of α may depend on the mission. Thus, concepts failing an α criterion for one mission may qualify for another mission. In no way, however, are the questionable concepts on the same level of acceptance as the concepts that are already expected to satisfy the fundamental criterion.

In summary, when underdeveloped concepts are competing with more mature concepts, one can still establish goal-oriented down-selection criteria, such as $\alpha < \alpha_{fission}$. Concepts can then be judged at any time based on whether their inherent physical limitations make it impossible to satisfy the criteria. By eliminating these concepts, NASA can concentrate its limited resources on the concepts that may ultimately prove useful.

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